




Sidedness of Divergence as a Key to Understanding Southern Ocean Upwelling in the Overturning Circulation of the Oceans

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Abstract

Sidedness of divergence helps resolve a present discordance in our understanding of upwelling in the Southern Ocean, and thus it contributes to the evolving recognition of the oceans' overturning circulation. Divergence can be two-sided (one water mass rises and moves apart in two flows, as is commonly envisioned) or one-sided (one water mass rises and moves away from another that does not move in the opposite direction). Upwelling in the Southern Ocean can be envisioned as a one-sided divergence north of a two-sided divergence. In the more northern one-sided divergence, deep to intermediate waters above or from North Atlantic Deep Water (NADW) upwell into the Antarctica Circumpolar Current (ACC) and move north. In the more southern and two-sided divergence, North Atlantic Deep Water (NADW) upwells and diverges southward into the Antarctic Coastal Current (ACoC) or Polar Current (PC) and northward into the ACC, mixing with the waters upwelled in the northern divergence. Understanding the northern upwelling as one-sided and the southern as two-sided thus eliminates an either/or conundrum that has evolved in the literature. It also allows the two modes of Southern Ocean upwelling (northern in the ACC and southern in the Antarctic Divergence) to be seen in the same comparative light as the two modes of upwelling postulated at global scale (upwelling in the Southern Ocean and upwelling or vertical mixing in the Indo-Pacific): in each comparison, the former involves the greater flux of water, whereas the latter involves water richer in geochemical tracers indicative of greater time and/or distance traveled at depth.

Keywords: Convergence; Divergence; Upwelling; Southern Ocean; Antarctica Circumpolar Current; Antarctic Coastal Current; Polar Current; Antarctic Divergence, North Atlantic Deep Water; Circumpolar Deep Water; Overturning circulation; Atlantic meridional overturning circulation; Sidedness, Great Ocean Conveyor, Plate tectonics, Troposphere

Abbreviations: AABW: Antarctic Bottom Water; ACC: Antarctic Circumpolar Current; ACoC: Antarctic Coastal Current; CDW: Circumpolar Deep Water; DIC: Dissolved inorganic carbon; NADW: North Atlantic Deep Water; PC: Polar Current

Introduction

Different Views of Upwelling

The past four decades saw a competition between two views regarding the upwelling of deep water in the oceans' overturning circulation. The "Great Ocean Conveyor" model, which arose from studies of ^{14}C , nutrient, and O_2 concentrations, suggested that most of the water that sinks in the Atlantic Ocean upwells in the Indian and Pacific Oceans [1-3]. On the other hand, understandings called either "Meridional Overturning Circulation" [4] or "Global Overturning Circulation" [5], which were derived from both chemical data and modeling studies, suggested that most deep water from the North Atlantic and Antarctica upwells in the

Southern Ocean [4,6]. In the last decade, the latter view has largely supplanted the former [6], in that Meridional or Global Overturning Circulation with its upwelling in the Southern Ocean involves the greatest flux [6-8], whereas the "Great Ocean Conveyor" with its upwelling in the Pacific can only be said to involve the greatest time and greatest distance of travel at depth.

Meridional or global overturning circulation can be further parsed according to where upwelling is thought to occur within the Southern Ocean, or (if it is in two locations) where it is most significant. Many papers invoke upwelling in the Antarctic Divergence, the divergence of surface water northward in or into the Antarctica Circumpolar Current (ACC) and southward in or into

the Antarctic Coastal Current (ACoC) or Polar Current (PC). This divergence is caused by Ekman transport driven by the westerlies and polar easterly winds, respectively (hence the ACC and ACoC/PC are also termed the West Wind Drift and East Wind Drift, respectively). Many papers specifically invoke the ACC and ACoC/PC and/or westerly and easterly winds in the Antarctic Divergence to explain upwelling of Circumpolar Deep Water (CDW) [9-18]. The Antarctic Divergence has been invoked to explain waters poor in ^{13}C [19], poor in ^{14}C [20], rich in Si [21], poor in O_2 and rich in DIC [22], rich in methylated Hg [23], and poor in dimethyl sulfoniopropionate [24] that indicate upwelling of deep water. These papers collectively indicate upwelling south of 60°S (Figure 1). One paper began by declaring that the Antarctic Divergence, which it specifically located at the boundary of the easterly and westerly winds, “plays a central role in the meridional overturning circulation” [12], and another characterized the Antarctic Divergence as “a relatively strong upwelling system” and mentioned no other divergence-driven upwelling in the Southern Hemisphere [18]. In support of that view, chemical data along transects extending from Antarctica to as far north as 45°S found no evidence of upwelling north of 60°S [19,23],

or at most evidence of less notable upwelling at 55°S [20,22].

An alternate location for upwelling of CDW in the Southern Ocean is in the ACC beneath the westerly winds, and thus north of the Antarctic Divergence. In a section on “Southern Ocean Upwelling”, one book on upwelling cited “meridional variation of the strength of the Westerlies” as the driver for Ekman transport and upwelling [25]. A paper about “Southern Ocean upwelling”, while explaining the closure of the meridional overturning circulation, similarly presented Southern Ocean upwelling entirely in terms of processes within the ACC [4]. A paper about “Upwelling in the Southern Ocean” likewise explained that Southern Ocean upwelling happens because “the strength of the westerly winds, and therefore the Ekman transport, varies with latitude” with maximum transport to the north at 50°S , well north of the Antarctic Divergence (Figure 1) [6]. A paper about “The Energetics of Southern Ocean Upwelling” similarly introduced upwelling as a process within the ACC driven by westerly winds [26]. Counter to the papers discussed in the previous paragraph, none of these four recent publications about Southern Ocean upwelling attributed upwelling to the Antarctic Divergence.

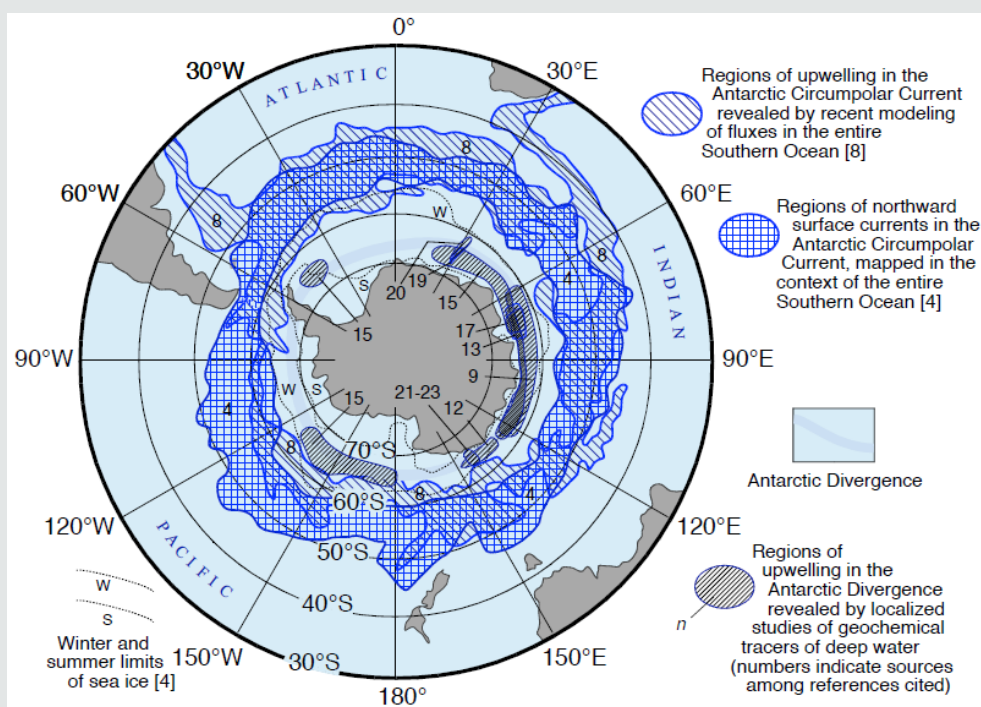


Figure 1: Map of the Southern Ocean showing regions of upwelling reported in the literature. Fields with coarse hachures and outlined with broad blue curves at $45\text{--}60^\circ\text{S}$ show locations of upwelling in the Antarctic Circumpolar Current, and fields with fine hachures and outlined with thin black curves poleward of 60°S show documented locations of upwelling in the Antarctic Divergence. The former are identified by water movement and the latter are identified by physical and/or geochemical measurements; the former are whole-ocean inferences whereas the latter are localized to tracks of cruises or locations of fixed devices. The results of Hayakawa et al. [15] are limited to upwelling south of the Antarctic Divergence.

The difference between these two views of the location of Southern Ocean upwelling, one in the Antarctic Divergence and the other in the ACC, might be ascribed simply to a difference in focus: many of the papers listed above describing upwelling in the Antarctic Divergence focused on tracers of deep water long isolated from the sea surface and thus on upwelling per se,

whereas the papers describing upwelling in the ACC were focused on the meridional overturning circulation and thus on transport northward (away from the Antarctic Divergence) to return water via the upper limb of the overturning system. However, a 2013 summary by Lynn Talley [5] provided a resolution based on water movement as well as observer focus, in that NADW of considerable

age upwells nearer Antarctica whereas other deep waters (e.g., the Upper Circumpolar Deep Water [27]) upwell farther north in the ACC. A large proportion of the NADW upwelling in the Antarctic Divergence moves southward and sinks in the formation of AABW, with only some upwelled NADW moving northward, whereas most of the water upwelled in the ACC moves north through various currents in the upper limb of the Meridional Overturning Circulation.

This article follows on Talley’s 2013 summary [5] by placing the dichotomy of Southern Ocean upwelling in a broader interdisciplinary perspective, that of differences in sidedness of divergence. Sidedness of convergence and divergence (Figure 2) is a concept that has been useful in understanding plate tectonics and,

to a lesser extent, atmospheric circulation. This article will propose that sidedness can also be useful in understanding patterns of ocean circulation.

Sidedness of Convergence and Divergence

In studies of the troposphere and the oceans, convergence and divergence are commonly understood to be two-sided (Figures 2A & 2B & 2G & 2H). In this understanding, convergence implies that two masses or flows come together from opposite directions, and the resulting combination moves away from the Earth surface (the interface of the atmosphere with land and sea) (Figures 2A & 2B). Two-sided divergence similarly implies that a mass moves toward the Earth surface and splits into two flows that move away in opposite directions (Figures 2G & 2H).

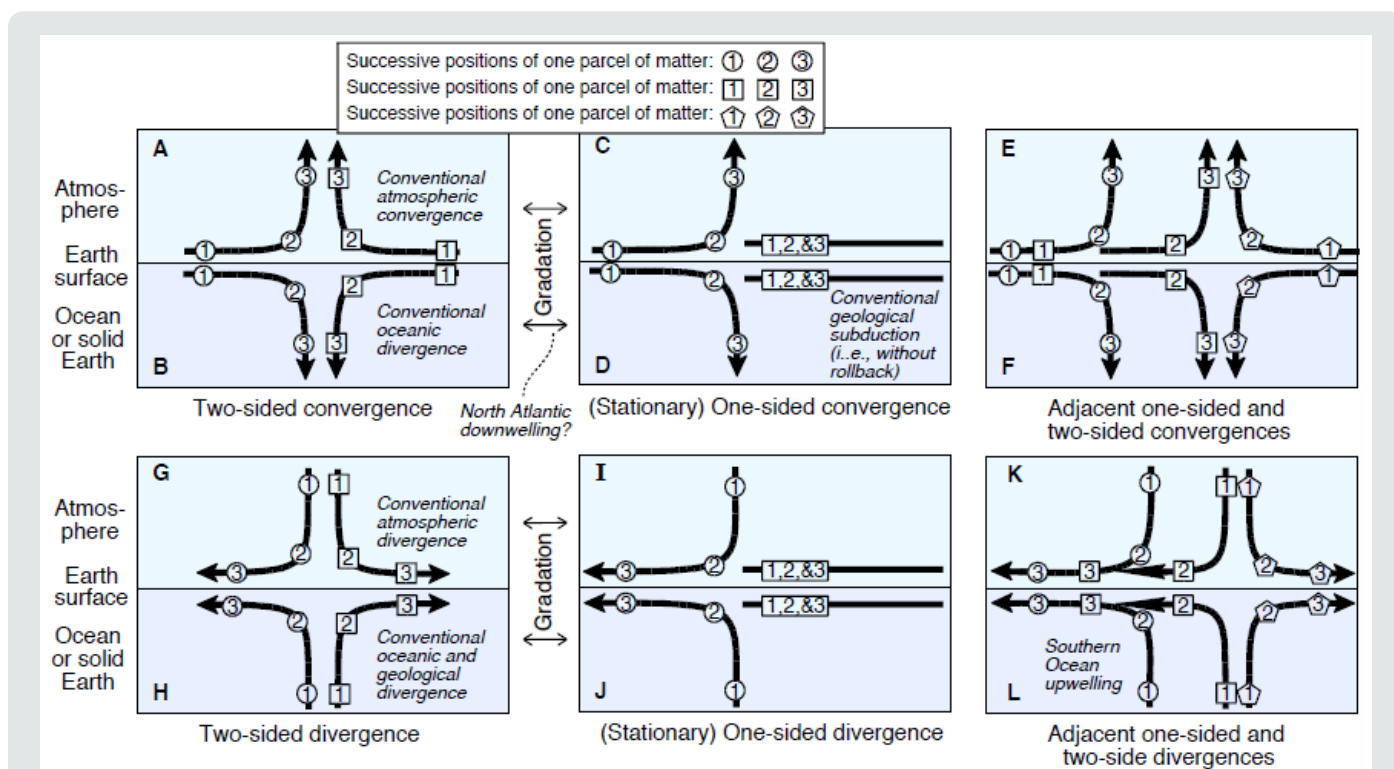


Figure 2: Twelve vertical cross sections illustrating possible modes of convergence (upper three panels, Parts A to F) and divergence (lower three panels, Parts G to L) in the atmosphere (upper half of each panel, Parts A, C, E, G, I, and K) and oceans or solid Earth (lower half of each panel, Parts B, D, F, H, J, and L). The figure is best viewed as a table of twelve kinds of motion, with atmosphere over ocean or solid Earth simply to facilitate recognition; any one style of atmospheric motion need not be paired in nature with the oceanic or solid-Earth motion below (e.g., D does not dictate C). Seven italicized labels show styles of motion recognized in nature. Convergence and divergence are most commonly envisioned as two-sided, as in leftmost two panels (A, B, G, and H), but one-sided convergence is the only known mode of subduction (convergence) in the solid Earth (D). Combination of one-sided and two-sided divergence (L) is this article’s explanation of Southern Ocean upwelling.

In contrast, geologists and solid-Earth geophysicists (henceforth “geoscientists”) have concluded that convergence in the solid Earth is one-sided (Figure 2D) [28]. Seismological evidence has demonstrated that, where two tectonic plates come together, one moves away from the Earth surface (it sinks) and the other does not [29]. This difference presumably arises because the much greater viscosity of the solid Earth compared to that of the oceans and atmosphere precludes the mixing inherent to

two-sided convergence into one flow. One-sided convergence is also sometimes observed in the troposphere, specifically during Northern-Hemisphere summer over eastern Asia, when the Southern-Hemisphere Hadley Cell becomes so large and migrates so far north that it consumes the northern Hadley Cell to eliminate the usual Inter-Tropical (two-sided) Convergence Zone in favor of a one-sided convergence [30].

One-sided and Two-sided Divergence in the Southern Ocean

The examples of one-sided convergence encountered by geoscientists (and to a lesser extent by atmospheric scientists) provide a conceptual model by which to envision one-sided convergence and one-sided divergence in the oceans, and specifically to address the seeming conundrum of upwelling and divergence in the Southern Ocean. Specifically, two styles and zones of divergence/

upwelling seem to combine in the Southern Ocean (Figure 2L). In the more northern zone, deep to intermediate waters upwell and largely turn north into the ACC in a one-sided divergence. In the more southern zone, deep water (mostly if not entirely NADW) upwells in a two-sided divergence, the Antarctic Divergence, with the southward flow ultimately sinking off Antarctica to contribute to Antarctic Bottom Water and the northward flow mixing with upwelled water of the northern upwelling zone to move still farther northward in the ACC (Figure 3).

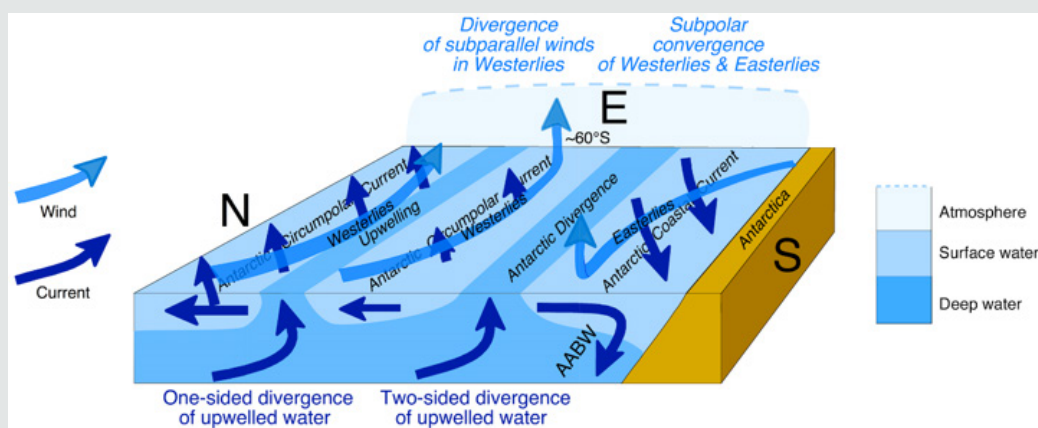


Figure 3: Explanation of upwelling of Circumpolar Deep Water around Antarctica in terms of two divergences of differing sidedness. This sketch applies the scheme in Figure 2L to the specific case of the Southern Ocean. The northward flux of upwelled water from one upwelling mass to its neighbor to the north is also suggested by Hayakawa et al. [15] and Figure 3 of Tamsitt et al. [8]. AABW = Antarctic Bottom Water.

The upshot of this view of upwelling in the Southern Ocean is that both of the communities discussed in the second and third paragraphs of this paper are at least qualitatively correct (and thus neither is required to avoid mention of the other). The remaining question is which upwelling zone contributes a greater flux to the surface limb of the meridional overturning circulation, akin to the distinction between the Meridional or Global Overturning Circulation and the Great Ocean Conveyor made in the first paragraph of this article. Recent modeling [8] indicates that upwelling from 42°S to 58°S in the ACC greatly dominates the total upward flux. Even more informatively, studies of dissolved inorganic carbon (DIC) show that the greatest concentration of DIC in upwelling water is in the Antarctic Divergence poleward of 60°S [22], but the greatest flux of CO₂ to the atmosphere is in the ACC at 50°S to 60°S [6]. Upwelling water in the Antarctic Divergence, with its chemical evidence of considerable time at depth [19-24], may (like the deep waters of the eastern Pacific in the Great Ocean Conveyor model) have spent greater time at depth and bring nutrient-rich water to the surface, but it is clearly volumetrically less significant than the waters upwelled in the ACC.

With that said about the present, students of either past or future circulation must bear in mind that recent modeling suggests that weakened Southern Ocean winds could cause a change from dominance of upwelling there to dominance by Indo-Pacific equatorial upwelling [31]. Alternately, modeling suggests that a

shift of the westerlies to the south could diminish Southern Ocean upwelling [26] (although the authors warn that their simulations run for only 50 model years and therefore may not reach equilibrium).

One-sided and Two-sided Convergence in the North Atlantic

Sidedness of convergence, rather than divergence, may also be a concept useful in understanding the overturning circulation at its undisputed northern extreme, in the North Atlantic. The formation of deep water masses there was once understood in terms of isopycnic mixing of saline water from farther south in the Atlantic with cold water at least in part from the Arctic [32], and this view of a two-sided North Atlantic convergence persists in current textbooks [33]. However, many recent depictions of the overturning circulation present the sinking to form deep water in the North Atlantic as the result of high-latitude cooling of saline water [34-36]. The latter view would suggest one-sided convergence akin to that seen by geologists (Figure 2D), although some form of downwelling intermediate between two-sided (mixing) and one-sided convergence is conceivable as well (Figure 2).

Conclusion

One's view of upwelling in the Southern Ocean need not be constrained to an either-or choice of upwelling at 42-58°S in the Antarctic Circumpolar Current or at 60-68°S in the Antarctic

Divergence of the Antarctic Circumpolar Current and the Antarctic Coastal Current or Polar Current. Instead, application of concepts from other fields allows upwelling in the Southern Ocean to be reconciled as a one-sided divergence at 45-58°S in the ACC and a two-sided divergence of the ACC and ACoC or PC at 62-68°S, with northward flow of the latter divergence mixing with the northward flow of the former to form the upper limb of the Meridional Overturning Circulation. However, the two upwellings are not evenly matched in multiple respects, in that upwelling in the ACC is presently the much larger flux, whereas upwelling in the Antarctic Divergence delivers nutrient-rich water suggestive of greater time at depth in its travels.

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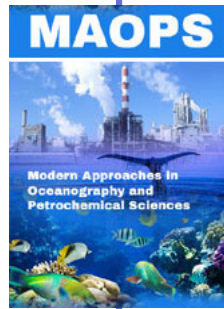
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